Development of Thin-Film Multijunction Thermal Converters at NIST*

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Abstract

This paper gives an overview of the development of thin-film multijunction thermal converters (FMJTCs) at the National Institute of Standards and Technology (NIST). A historical perspective of film thermal converters is presented, followed by descriptions of the motivation, fabrication processes, physical characteristics and the electrical properties of the FMJTCs produced at NIST. Integrated micropotentiometers which incorporate FMJTCs, and thermal converters, produced by an alternative fabrication technology using a CMOS foundry, are also described. The paper concludes with a report on the present status of the FMJTC project and future directions.

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Introduction

There has been considerable interest in the use of micro-machining of silicon and photo-lithography on thin films to produce various types of sensors. This paper describes the project at NIST to develop new multijunction thermal converters (MJTCs) and related devices using those technologies. The goal was to produce MJTCs with performance comparable to conventional wire MJTCs in the audio-frequency region but with greater overall frequency and current ranges and at lower cost. Such new MJTCs could potentially be useful in commercial instruments as well as for laboratory standards. Several other projects or proposals to develop thin-film MJTCs had been reported when the NIST effort began in earnest in 1990 [1-4].

Construction

Low ac-dc difference, small dc reversal error, and high thermal efficiency have been achieved by the thermal design, physical arrangement, and careful selection of materials for the heater and thermocouples. The basic elements of the FMJTCs are a thin-film heater supported on a thin dielectric membrane, a silicon frame surrounding the structure, and thin-film thermocouples positioned with hot junctions near the heater and cold junctions over the silicon [5]. Figure 1 shows a cross section of an FMJTC. The heater and thermocouples are sputter-deposited and photolithographically patterned. Photolithographic fabrication of thin-film MJTCs allows for accurate dimensioning of the heater and thermocouples. The planar design and the spacing between the thermocouples and the surrounding heat sink reduce the temperature variations along the heater in the region sampled by the hot junctions. Contributions to ac-dc difference from Thomson and other effects are further reduced by the appropriate choice of heater alloy.

To provide mechanical stability and good thermal efficiency, a thin, multilayer membrane has been used to support the heater structure and the thermocouple hot junctions. The heater was placed on the membrane, and the silicon back-etched away underneath to reduce both conductive heat loss and the dielectric loss and therefore reduce the ac-dc difference and voltage or current coefficients. Fabrication of the membrane presented the greatest challenge of all the processing steps. Low overall stress and low dielectric loss have been achieved in the membrane by the use of balanced layers of SiO_2 and Si_3N_4. If the membrane is in compression, such as for plain oxide, wrinkles will appear. Figure 2 shows such a membrane in compression viewed through the opening in the silicon. The dimensions of this membrane are about 2 mm x 4 mm. The dark band surrounding the membrane is the beveled face of the silicon. If the membrane is in tension, such as for plain nitride, it breaks very easily. If the stress is unbalanced in a composite membrane, it will curl when broken as shown in Fig. 3. If the net stress is very low or well balanced, even a broken membrane will remain approximately in its original plane. A remarkable example is seen in Fig. 4.

The silicon frame provides a good heat sink for the thermocouple cold junctions and is mounted directly on an aluminum oxide substrate to provide an even more effective heat sink. To reduce the error due to Peltier effect, the contact pads for wire bonded leads are placed over the silicon frame. These thermal and physical design characteristics also contribute to very small dc reversal errors.

Custom packages consisting of aluminum oxide substrates patterned with thick-film conductors have been designed and fabricated to provide long-term stability, small distributed capacitance and inductance, and minimum skin effect through the use of all non-magnetic materials. These packages preserve the inherent ac-dc differences of the thin-film MJTCs.

Geometric Designs

Several different geometric designs have been developed incorporating variations in heater geometries and thermocouple positions. They include a linear heater which can be assembled in a coaxial geometry, a bifilar heater, and a short, wide heater designed for currents of 1 A or higher. Some converters contain thermocouples adjacent to the heater while others have thermocouples that are located directly over the heater separated by a layer of SiO_2. A photograph of a coaxial FMJTC is shown in Fig. 5. This chip has 64 thermocouples and a membrane of about 2 mm x 4 mm. This thin-film technology lends itself to the production of a variety of specialized or dedicated structures, such as a differential device containing two converters, each consisting of a heater with its membrane and thermocouples, on the same chip. The differential pair of multijunction converters can be connected to provide either a single output that is nulled when the two signals are matched, or separate output signals suitable for individual processing.

For the measurement of millivolt and microvolt signals, micropotentiometers are used. Micropotentiometers consist of thermoelements with low valued resistors in series with the heaters. New integrated micropotentiometers containing thin-film MJTCs and thin-film output resistors fabricated as an integrated structure on the same silicon chip have also been developed under this project [6]. Several different types of these devices have been made. Most were single-range versions with a 5 mA MJTC combined with either a 20 Ω, 2 Ω, or 0.2 Ω output resistor. Others were multirange devices with as many as five voltage ranges from 1 mV to

200 mV. Figure 6 shows a multirange integrated micropotentiometer with a membrane of about 2 mm x 2 mm.

Performance

Representative results on the FMJTCs include ac-dc differences of sub-μV/V values at 1 kHz, a few μV/V or less from 50 kHz up to 100 kHz, and several tens of μV/V at 1 MHz for a bifilar-heater MJTC used as a voltage converter and generally lower as a current converter up to 100 kHz. The dc reversal errors are only a few μV/V or less, as expected. Various versions of the FMJTCs are usable up to 100 MHz. Several characteristics improve at lower ambient pressures and lower temperatures. Output emf and the thermal time constant increase about eight times at 0.13 Pa making a more efficient converter and reducing the low-frequency ac-dc difference at 100 Hz and below. The large increase in efficiency at low pressure enables vacuum mounted MJTCs to be used effectively at currents as low as 1 mA and voltages below 100 mV. Figure 7 shows the variation in output emf of a FMJTC from atmospheric pressure down to about 15 mPa. Table 1 presents ac-dc difference data for a representative coaxial FMJTC with a constantan heater as both a voltage and current converter. This particular FMJTC has a heater resistance of about 100 Ω and thermocouple resistances of about 8 kΩ per thermocouple bank. Other FMJTCs from the same production run have thicker thermocouple metals to reduce the output resistance of the device to about 3.7 kΩ per bank, and Evanohm[†] heaters of about 112 Ω. Tests on these devices indicate characteristics similar to the given example.

For instrumentation applications, the FMJTCs are suitable for operation over a wide range of output emfs, as high as 0.5 V. The ac-dc differences of the thin-film, integrated micropotentiometers are generally close to the presently available calibration uncertainty at audio frequency but range up to several percent up to 100 MHz.

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† The use of trade names in this paper does not imply endorsement or recommendation by NIST.

Other Applications

Preliminary studies indicates that FMJTCs may be useful as vacuum sensors and infrared detectors. In addition, two other novel applications are under study which rely strongly on the unique structure of the FMJTC.

In collaboration with Prof. Manfred Wuttig and Dr. Quanmin Su, Deptartment of Materials and Nuclear Engineering, University of Maryland, the kinetic energy of atoms and the stress of thin-films have been evaluated during sputter deposition of Au using FMJTCs. The procedure relies on both the high thermal sensitivity of the FMJTC and the low inertia of the membrane. This technique may lead to the development of in-situ, real time measurement of kinetic energy and stress during thin-film deposition. Furthermore, in collaboration with Dr. David Blackburn of the NIST Semiconductor Electronics Division, the measurement of gas flow at very low velocity has been studied. The procedure relies again on the high thermal sensitivity of the FMJTCs and the ability to design custom geometry for the application.

CMOS-foundry Design and Fabrication

The MJTCs described above require custom processing; however, MJTCs have also been fabricated in collaboration with Dr. Michael Gaitin of the NIST Semiconductor Electronics Division, using CMOS-foundry compatible micromachining [7,8]. The CMOS-foundry compatible micromachining technique is based on the incorporation of open areas in the mask layout that bares the silicon surface. After receipt from the foundry, the silicon under the open area is etched away leaving a pit and suspended structure.

The technique used in this project permitted only layers of polysilicon and aluminum. These layers are encapsulated in SiO_2 that act both as the protective barrier to the etchant and as the mechanical support. The polysilicon heater resistor and the hot thermocouple junctions were suspended on a web or cantilever created by etching a pit in the silicon about 150 μm x 150 μm in area. The thermocouples are made of aluminum-polysilicon. The choice of materials limits the performance of these CMOS-foundry MJTCs; however, they offer extremely small size, high output emf, very low cost, and the opportunity for easy inclusion with other circuitry for commercial applications.

Present Status and Future Directions

An area of particular interest for further development is the reduction of low-frequency errors. When FMJTCs are mounted in a vacuum, their thermal time-constants increase by nearly a factor of ten bringing some of the chip designs generally within the performance acceptable around 20 Hz. Vacuum mounts are regarded as essential for these converters and an effort is being made to provide suitable vacuum packages. The possibility of increasing the thermal mass of the heater with a high-quality dielectric material is also being studied. Because the FMJTCs are so efficient, they can be used at quite low heater temperatures where the low-frequency errors are significantly reduced, sometimes by several factors of ten. Useful converters can be made by incorporating appropriate series or shunt resistors to provide a higher voltage or current range with less current through the heater. Work is continuing to incorporate this type of compensation on the chip. It is anticipated that errors at low frequencies can be substantially reduced in the next generation of devices.

Work is also continuing to reduce the output resistance of the thermocouples. The resistances are reduced by sputtering thicker metals for the couples and by adjusting the thermocouple geometry. The maximum deposited thickness permitted without damage to the membranes has not yet been determined and is presently under study. Some FMJTCs have thermocouple output resistances smaller than 1 kΩ per side, however, the output resistances of coaxial and bifilar devices with as many as 32 couples per side are much higher. Recent fabrication runs have produced these types of chips with output resistances as low as 3.2 kΩ per thermocouple bank, a reduction of a factor of about two over earlier versions. Substantial further reductions are believed to be possible.

High-current FMJTCs with heaters suitable for 1 A have been produced and studied as individual chips as well as in a high-current module containing up to six high-current devices. Measurements at currents up to 6 A have been made [9]. These devices show promise in supplementing or even replacing the traditional thermoelements used for the calibration of thermal current converters and transfer shunts. Work is underway to improve the performance of these devices, particularly at low frequencies, and to produce current modules rated at 20 A or more.

Measurements of ac-dc difference and square-law characteristics on a FMJTC at temperatures as low as 10 K show the devices continue to be useful at low temperature where thermoelectric errors would be expected to decrease. Some characteristics have been observed to improve below 100 K, and a program to study the performance of FMJTCs at low temperatures is presently underway.

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<u>Figure Captions</u>

Fig 1. Cross section of a thin-film multijunction thermal converter.

Fig. 2. Membrane in compression viewed through the opening in the silicon. The dimensions of this membrane are about 2 mm x 4 mm.

Fig. 3. Curled composite membrane with unbalanced stress.

Fig. 4. A broken membrane with very low, well balanced stress. Note the membrane with a thickness of less than 1 μm remains approximately in its original plane.

Fig. 5. Photograph of a coaxial FMJTC. The membrane is about 2 mm x 4 mm.

Fig. 6. Multirange integrated micropotentiometer with a membrane of about 2 mm x 2 mm.

Fig. 7. Variation in output emf of a FMJTC from atmospheric pressure down to about 15 mPa.

Table Headings

Table 1. Representative data for a coaxial, constantan-heater FMJTC as a voltage and current converter at various input levels and frequencies.

Applied Voltage	Ac-dc Difference (μV/V) as thermal voltage converter					
Volts	100 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
0.5	+25±4	0±3	+7±3	+13±4	+26±8	+40±12
1.0	+8±4	-2±3	+6±3	+12±4	+24±8	+40±12
1.5	+18±4	-2±3	+2±3	+8±4	+20±8	+35±12
2.0	+48±4	-4±3	0±3	+7±4		

Applied Voltage	Ac-dc Difference (μV/V) as thermal voltage converter					
Volts	100 kHz	200 kHz	300 kHz	500 kHz	800 kHz	1 MHz
0.5	+40±12	+78±26	+112±26	+166±26	+235±26	+279±26
1.0	+40±12	+63±26	+94±26	+154±26	+237±26	+288±26

Applied Current	Ac-dc Difference (μA/A) as thermal current converter								
mA	100 Hz	400 Hz	1 kHz	3 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10	+34±7	+2±7	0±7	0±7	-1±7	+1±7	+1±9	+3±11	+5±21
20	+126±7	+10±7	+4±7	+3±7	+2±7	+2±7	+3±9	+10±11	+4±24